Measurement of Free Nucleon Structure and Nuclear Modifications Using Deuteron Tagged DIS at the EIC

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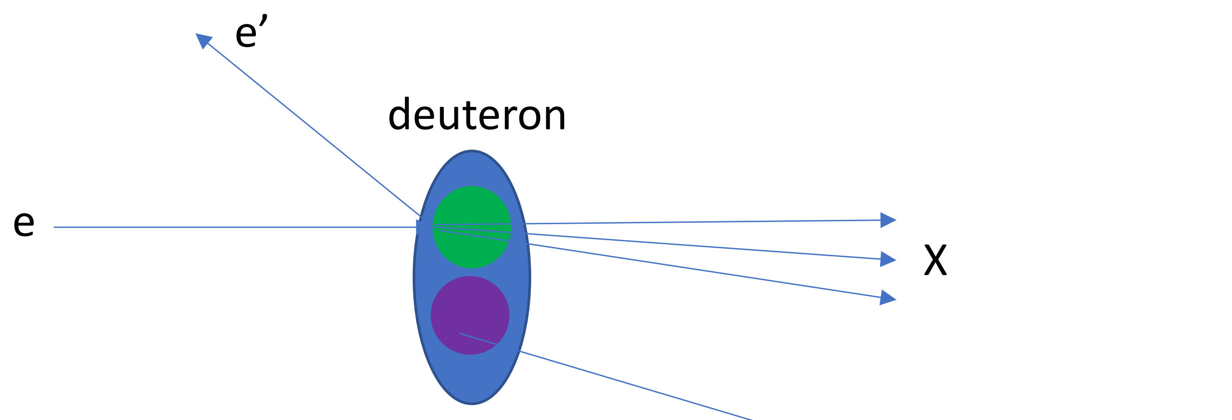
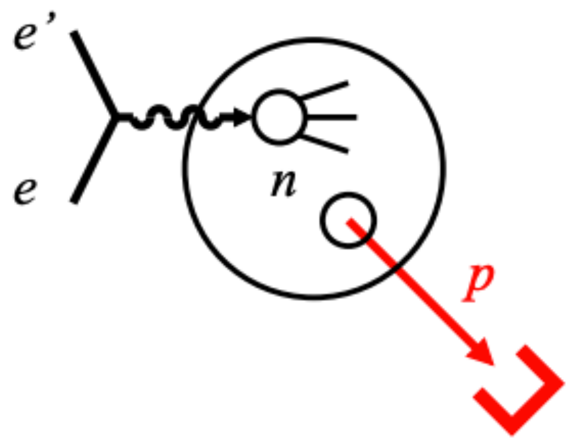
Scope of This Study

- Perform tagged DIS measurements on unpolarized deuteron at the EIC.
  - Provides access to the free neutron structure function.
  - Study nuclear modifications of both nucleons in the deuteron.
  - EMC effect, anti-shadowing, etc.
- Utilizing tagging provides experimental access to dial the kinematics between the “free” and “modified” nucleons.



deuteron rest frame

First Application: Free Neutron F2



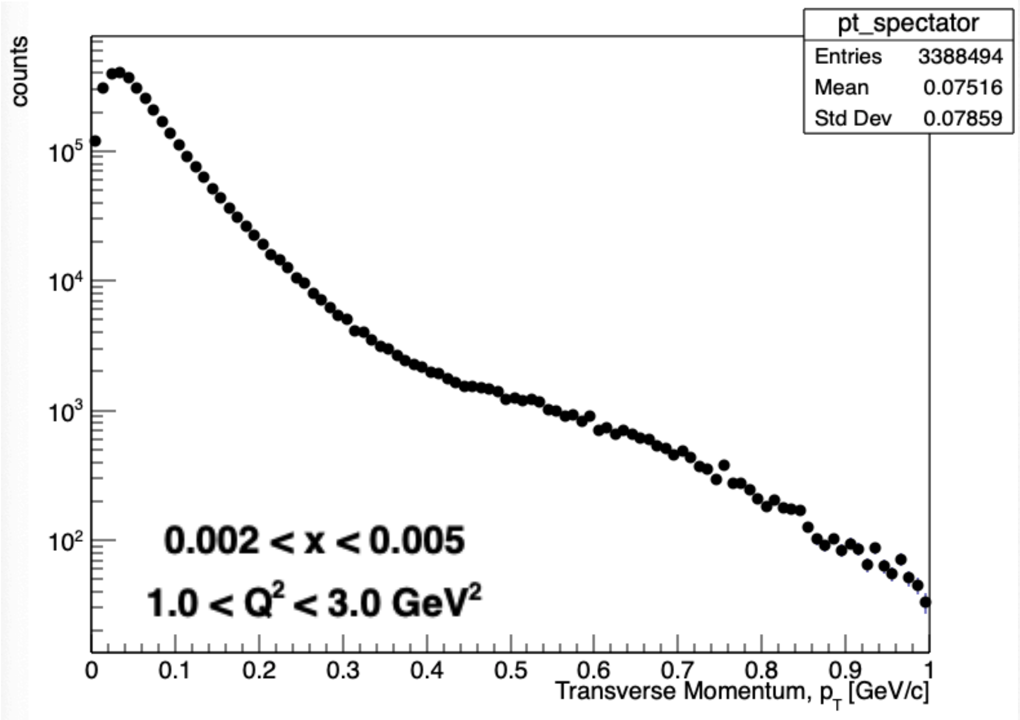
- Why the neutron?
  - Flavor separation, baseline for nuclear modifications
- What makes the free neutron structure hard to measure?
  - Can only access neutrons *in a nucleus.*
  - Includes nuclear binding effects, Fermi motion, etc.
- <u>Two options:</u> Inclusive + theory (broad) or tagged measurements (differential).
  - Tagging "fixes" the nuclear configuration and allows for more differential study.
- On-shell extrapolation enables access to free nucleon structure (Sargsian, Strikman 2005).

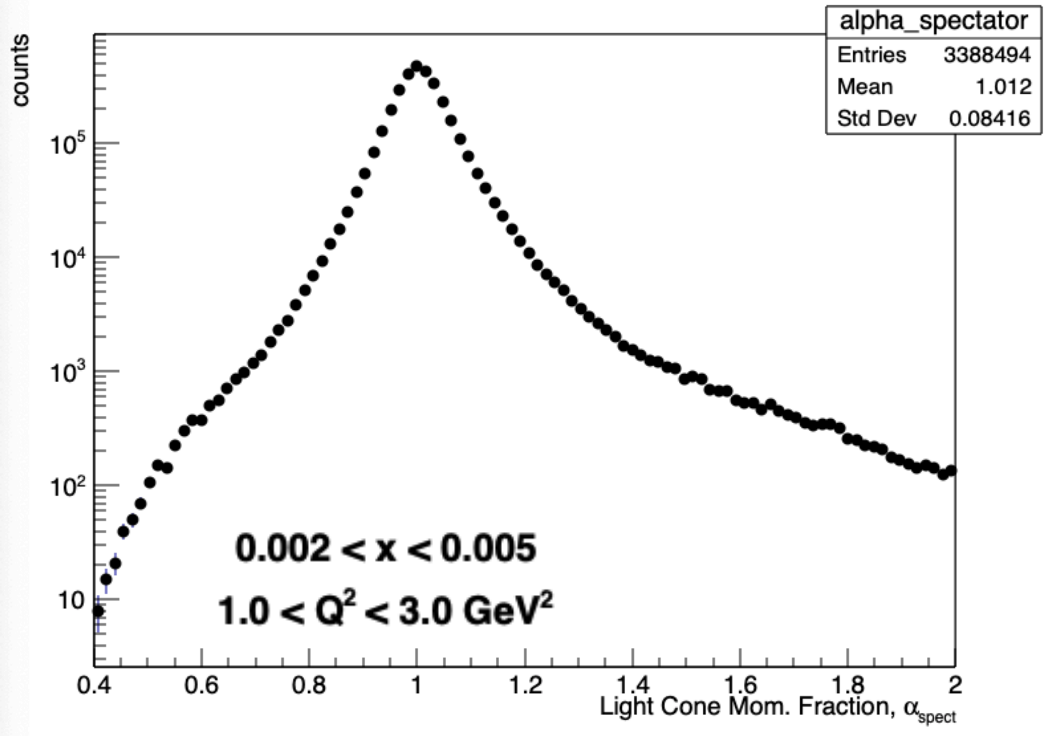
Preliminaries

- Previous fixed target experiments have measured the neutron F_2 at high-x.
  - (CLAS, Phys. Rev. Lett. **108**, 199902 (2012))
  - BONUS measurement had a lower pT cutoff ~ 70 MeV/c.
- Tagged DIS @ the EIC:
  - In a collider, can tag spectators down to pT ~ 0 MeV/c -> Enables extraction of free neutron structure function via pole extrapolation.
  - Can extend tagged DIS measurement to $x \lesssim 0.1$.
- Method will be first shown for measuring proton F_2 for validation, then the neutron results will be shown.
  - Detector effects will be added later to discuss prospects for measurement in the EIC detectors.

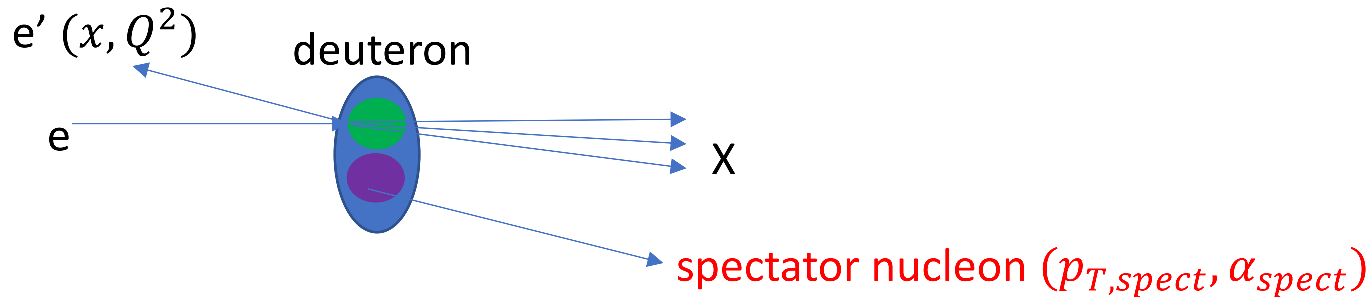
MC Generator: BeAGLE

- BeAGLE used to generate e+d 100M events @ 18x110 GeV/n.
  - Implements the light-front wavefunction of the deuteron.
  - Same setup was used for the BeAGLE paper (PLB 811, 135877 (2020)), just the DIS process.





Basic Method - Tagging



α_{spect}: light-cone momentum fraction

$$\alpha_{spect} \equiv \frac{2p^+_{nucleon}}{p^+_{nucleus}} = \frac{2(E_{spect} - p_{z,spect})}{M_d}$$

S_d: deuteron spectral function

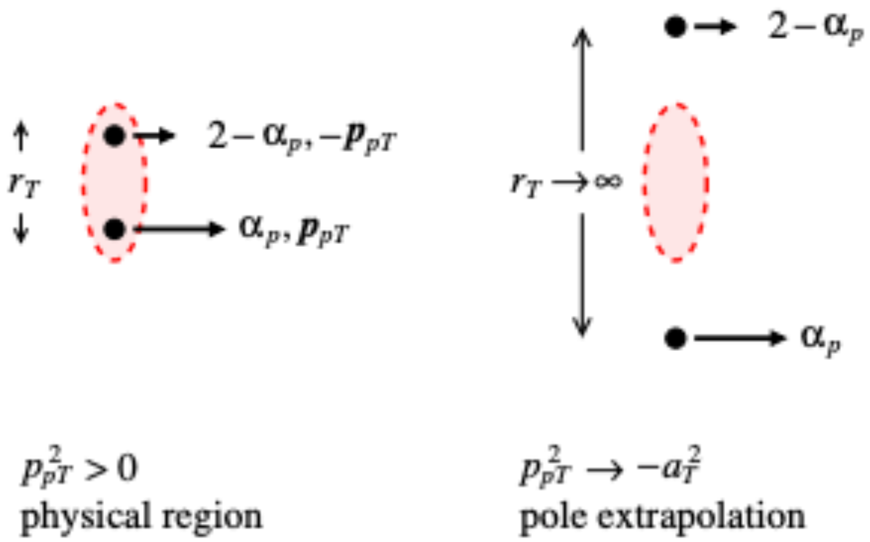
- Measure the cross-section differential on the spectator kinematics.
  - $\mathcal{F}_d(x, Q^2;\, p_{T,spect}, \alpha_{spect})$ is analogous to the standard HERA σ_r.
  - $\mathcal{F}_d\left(x, Q^2;\, p_{T,spect}, \alpha_{spect}\right) \propto\ S_d \times F_{2,nucleon}$

$$d\sigma = Flux(x, Q^2) \times \mathcal{F}_d \times \frac{dx}{2} dQ^2 \frac{d\phi_{e\prime}}{2\pi} [2(2\pi)^3]^{-1} \frac{d\alpha_{spect}}{\alpha_{spect}} \frac{dp^2_{T,spect}}{2} d\phi_{spect}$$

- Extract $\mathcal{F}_d$ differentially in $(p_{T,spect}, \alpha_{spect})$ by weighting with flux factor and constants.

Note: Integrating over the spectator variables returns the inclusive cross-section – an important cross-check!

Basic Method - pole extrapolation (arxiv:2006.03033)



- Once $\mathcal{F}_d$ is measured, multiply by the inverse of the pole of the spectral function to remove the pole dependence on the distribution.
  - The resulting distribution is F_2 as a function of $p_{T,spect}^2$.

$$\mathcal{F}_d \to \mathcal{F}_d \times \frac{\left(p_{T,spect}^2 + a_T^2\right)^2}{R}$$

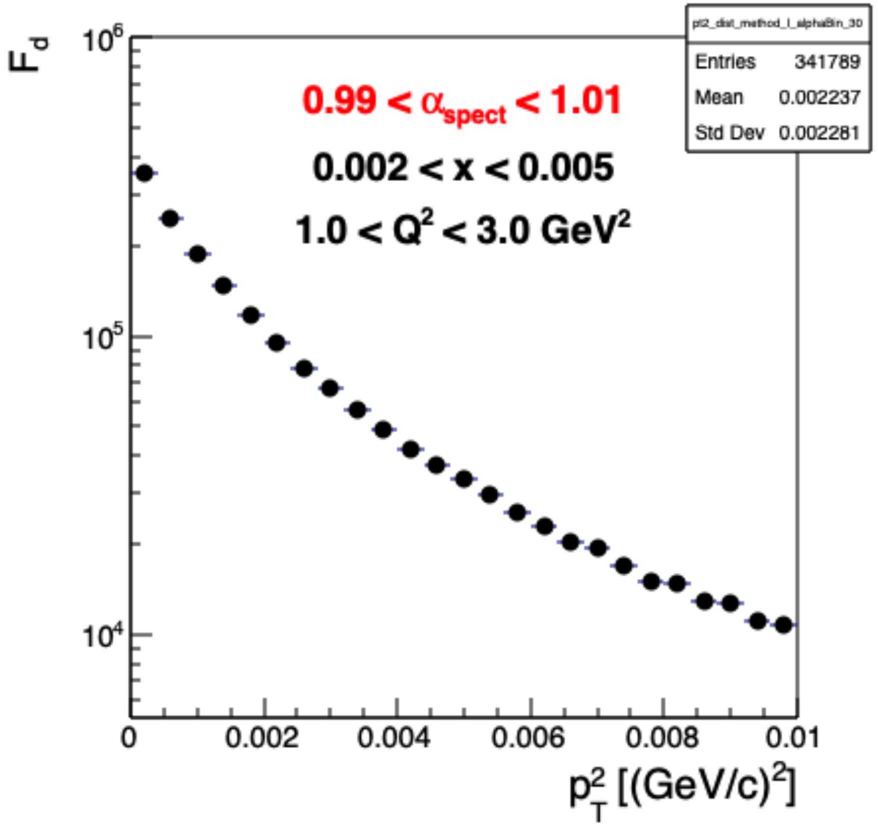
- Extrapolate to $p_{T,spect}^2 \to -a_T^2$ to extract F_2 to extract free nucleon F_2.

$$\frac{\left(p_{T,spect}^2 + a_T^2\right)^2}{R} = inverse\ pole\ of\ spectral\ function$$

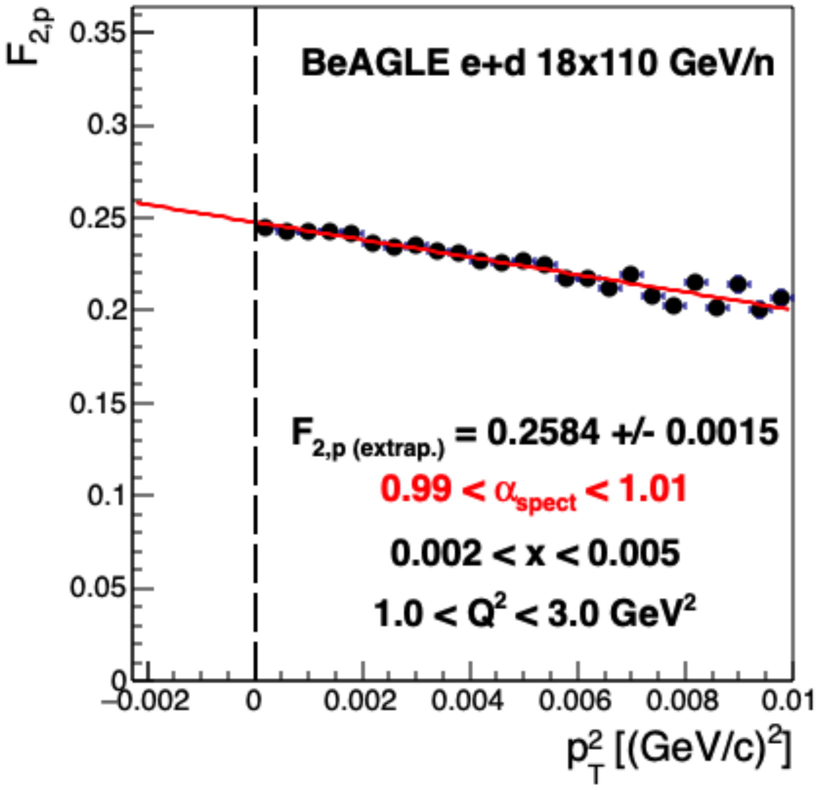
$$R = residue\ of\ spectral\ function$$

$$a_T^2 = position\ of\ pole$$

Basic Method (pole extrapolation)



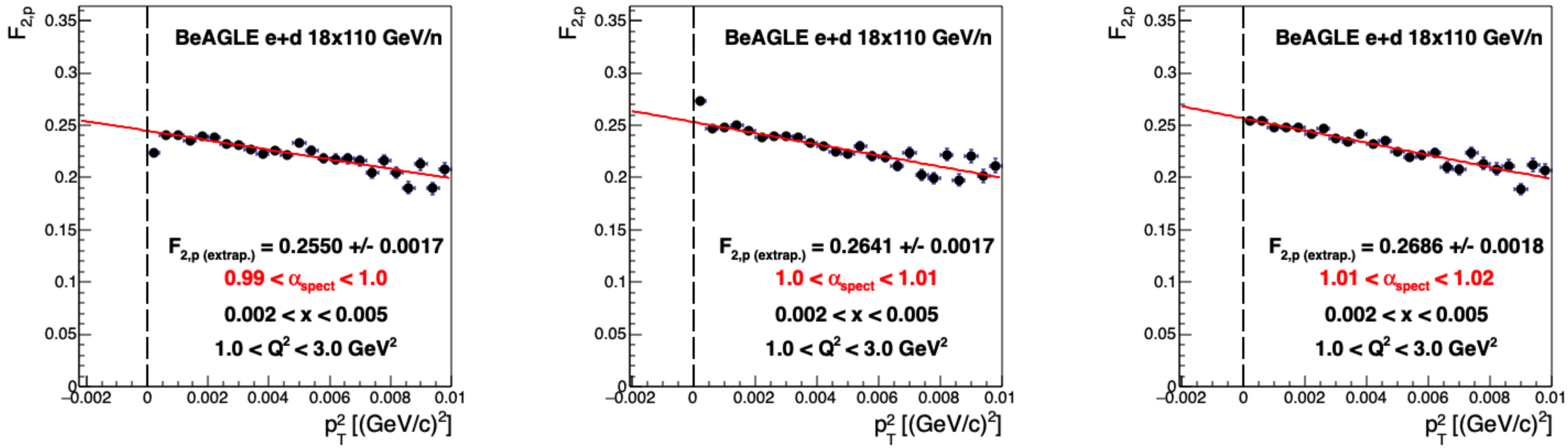
$$\mathcal{F}_d \rightarrow \mathcal{F}_d \times \frac{\left(p_{T,spect}^2 + a_T^2\right)^2}{R}$$



- Method eliminates nuclear binding effects.
- Resulting dependence on $p_{T,spect}^2$ is very weak and the extrapolation can be performed with a 1st-degree polynomial fit.

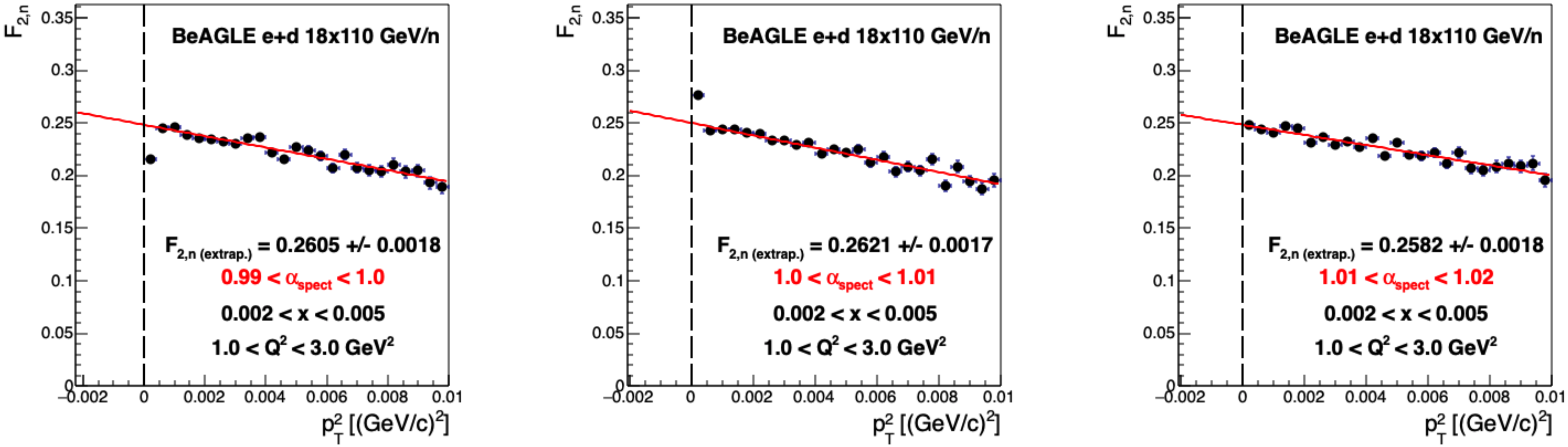
F_2 Proton

- Free proton structure function extracted from tagging (below plots) compared with input to BeAGLE (calculated with HERA inclusive method).
  - $\sigma_r = 0.279415$ +/- 0.000189
- First p_T^2 bin not used in fit.
- Detailed comparison: Work in progress.



F_2 Neutron

- Free neutron structure function extracted from tagging (below plots) compared with input to BeAGLE (calculated with HERA inclusive method).
  - $\sigma_r = 0.278514$ +/- 0.000189
- First p_T^2 bin not used in fit.
- Detailed comparison: Work in progress.



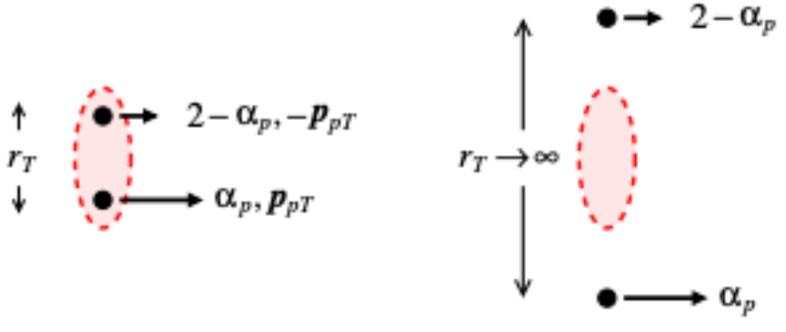
Summary

- Basic method of on-shell extrapolation demonstrated.
  - Method removes nuclear binding effects and FSI to yield access to free nucleon structure.
  - P_T dependence after pole removal is very smooth.
- Free structure functions extracted with tagging reproduce free nucleon input.
  - Need to finalize checks of extraction method for free proton and neutron F_2.
  - Accuracy of physics model input.
- Outlook and next steps.
  - Perform full GEANT simulations to establish experimental prospects for full physics program at the EIC.
  - Detector resolutions, acceptance, beam effects, etc.
  - Use tagging method to study nuclear modifications (EMC effect, anti-shadowing, etc.).

Backup

Basic Method (pole extrapolation; REF)

$$d\sigma = Flux(x,Q^2)\times \mathcal{F}_d \times \frac{dx}{2} dQ^2 \frac{d\phi_{e'}}{2\pi} [2(2\pi)^3]^{-1} \frac{d\alpha_{spect}}{\alpha_{spect}} \frac{dp^2_{T,spect}}{2} d\phi_{spect}$$



$p^2_{pT} > 0$
physical region

$p^2_{pT} \to -a^2_T$
pole extrapolation

- Once $\mathcal{F}_d$ is measured, multiply by the inverse of the pole of the spectral function to remove the pole dependence on the distribution.

$$\mathcal{F}_d \to \mathcal{F}_d \times \frac{\left(p^2_{T,spect} + a^2_T\right)^2}{R}$$

$$a^2_T = m^2_N - \alpha_{spect}(2-\alpha_{spect})\frac{M^2_d}{4}$$

$$R = 2\alpha^2_{spect} m_N \Gamma^2 (2-\alpha_{spect})$$

- Extrapolate to $p^2_{pT} \to -a^2_T$ to extract F2.